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Use of Minimum Groundwater Levels and Groundwater Abstractions for Assessing the Quantitative Status of Quaternary Groundwater Bodies in the Czech Republic

(Využití hladin a odběrů podzemní vody pro hodnocení jejich kvantitativního stavu v kvartérních HGR)

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Abstract: Water balance assessments are generally not performed for Quaternary groundwater bodies (GWBs) in the Czech Republic because it is extremely difficult to establish a simple groundwater balance in Quaternary sediments along major rivers. Groundwater inflows originate from adjacent groundwater bodies on valley slopes, from drainage of underlying groundwater bodies, from local infiltration of precipitation, or from induced infiltration from surface watercourses, where the amount of infiltrated water is negligible compared to streamflow. Conversely, monitored groundwater levels reflect the combined effects of all groundwater recharge mechanisms and groundwater abstraction (GWA).

To facilitate groundwater balance assessments, Quaternary GWBs were subdivided, where necessary, into smaller units (sub-regions) according to the estimated extent of major well fields and the configuration of boundary conditions. For each sub-region (or groundwater body), a representative groundwater-level (GWL) hydrograph was developed by averaging standardized monthly groundwater levels from all monitoring wells within the sub-region (sGWL).

For each sub-region, the minimum standardized groundwater level during the most significant drought periods (sGWLmin) and the historical evolution of groundwater abstraction were determined. By comparing sGWLmin recorded during droughts with different historical abstraction rates, both volumetric and GWL based criteria were established to define the conditions under which the quantitative status of groundwater in a sub-region can be considered good.

This methodology was applied to 64 of the 75 identified sub-regions. The remaining 11 sub-regions, characterized by insufficient abstraction records and GWL monitoring, required a site-specific assessment approach. Finally, the quantitative status of individual Quaternary GWBs was evaluated based on the assessments of their constituent sub-regions.

Keywords: groundwater balance – groundwater level – groundwater body

Abstrakt: Hydrologická bilance v kvartérních hydrogeologických rajonech (HGR) se v Česku neprovádí, protože je velmi složité provádět jednoduché bilancování podzemní vody v kvartérních sedimentech podél velkých řek. Podzemní voda přitéká ze svahů z okolních HGR, drénuje se z podložních HGR, infiltruje se v místě kvartérního HGR ze srážek nebo může přitékat z povrchového

toku, kde je množství vcezené vody vůči průtoku povrchové vody zanedbatelné. Monitorované hladiny podzemní vody naopak odpovídají výslednému efektu všech možných způsobů doplňování podzemní vody v kvartérních HGR a také jejich využívání. Pro snadnější bilancování podzemní vody, kde to bylo zapotřebí, byly kvartérní HGR rozděleny na dílčí části – subrajony. Rozdělení proběhlo podle předpokládaného dosahu velkých jímacích území a upořádání okrajových podmínek. Pro každý subrajon resp. HGR byl vytvořen vlastní generelní vývoj hladiny podzemní vody (HPV), který byl stanoven zprůměrováním standardizovaných měsíčních HPV ze všech vrtů v subrajonu (sHPV).

V každém subrajonu byla pro nejvýznamnější suchá období stanovena minimální sHPV (sHPVmin) a vývoj odběrů podzemní vody (POD). Porovnáním sHPVmin v období sucha a s různou velikostí historických POD bylo stanoveno množstevní a hladinové kritérium, při kterém stav podzemní vody v subrajonu lze považovat za dobrý. Tento přístup byl použit pro celkem 64 ze 75 subrajonů. Pro zbývajících 11 subrajonů s nedostatečným POD a monitoringem HPV bylo postupováno specificky. Na základě hodnocení kvantitativního stavu subrajonu bylo provedeno hodnocení kvantitativního stavu HGR.

Klíčová slova: Bilance podzemní vody – hladina podzemní vody – útvar podzemní vody

Introduction

In the Czech Republic, the annual quantitative assessment of groundwater resources in basic-layer groundwater bodies (GWBs) is based on the ratio of total groundwater abstraction (GWA) to natural groundwater resources. Natural resources are estimated from baseflow separated from total streamflow by the Czech Hydrometeorological Institute (CHMI 2025).

Although this approach is generally suitable for shallow and deep aquifers with limited interaction between groundwater and surface water, it is not readily applicable to Quaternary GWBs, where groundwater balance calculations are considerably more complex. In these aquifers, baseflow may substantially differ from actual groundwater discharge due to groundwater inflow from adjacent or underlying groundwater bodies or, conversely, groundwater outflow beyond the closing hydrological profile.

Groundwater resources in Quaternary GWBs vary over time depending not only on recharge conditions but also on the intensity of groundwater abstraction. Groundwater recharge originates from lateral inflow from adjacent groundwater bodies, upward drainage from underlying aquifers, local infiltration of precipitation, and induced infiltration from surface watercourses, where the infiltrated volume is generally negligible compared with stream discharge. Consequently, annual groundwater balance assessments based solely on baseflow are not performed for Quaternary GWBs.

Instead, monitored groundwater levels (GWLs) represent the integrated response to all groundwater recharge processes and groundwater abstraction. Therefore, GWLs are evaluated together with the evolution of baseflow in recharge areas and underlying GWBs, fluctuations in surface-water levels, and groundwater abstractions.

An important aspect of the methodology is the analysis of GWL fluctuations at individual monitoring wells and the comparison of fluctuations among wells with respect to their hydrogeological setting and dominant GWL response. The objective is to distinguish the effects of natural groundwater recharge from those of groundwater abstraction and to use these relationships as the basis for a methodological assessment of groundwater balance in Quaternary GWBs.

Many Quaternary GWBs contain several hydraulically independent well fields, while others are divided by major rivers. For this reason, a number of Quaternary GWBs were subdivided into smaller assessment units (sub-regions), each of which was evaluated independently.

Representative GWL Hydrograph in Quaternary GWBs

A total of 484 monitoring wells are used to observe groundwater levels in Quaternary GWBs, their immediate surroundings, and the underlying aquifers throughout the Czech Republic. Monitoring at 39 of these wells commenced in 2007 and 2008. Long-term GWL records spanning at least 30 years are available for 445 wells. Due to missing observations during the periods 1990–1994 and 2015–2020, 13 wells were excluded from the analysis. Consequently, the assessment presented here is based on GWL records from 432 monitoring wells.

To provide an overall characterization of GWL fluctuations across Quaternary GWBs, a representative GWL hydrograph was constructed. This hydrograph represents the average response of groundwater levels measured at all 432 long-term monitoring wells located within Quaternary GWBs, their adjacent areas, and the underlying aquifers.

In the annual groundwater status assessments conducted by CHMI, the 5th percentile of groundwater levels is considered the threshold for exceptional drought. Relative GWLs, as shown in the representative GWL hydrograph on Fig. 1, dropped below this threshold during the droughts of 1973 (and locally in 1974), 1983 (and locally in 1984), 1990–1994, 2003–2004, 2015–2020, and 2022–2023. These periods are hereafter referred to as major drought periods. Among them, the droughts of 1990–1994 and 2015–2020 were the longest and were associated with the lowest groundwater levels.

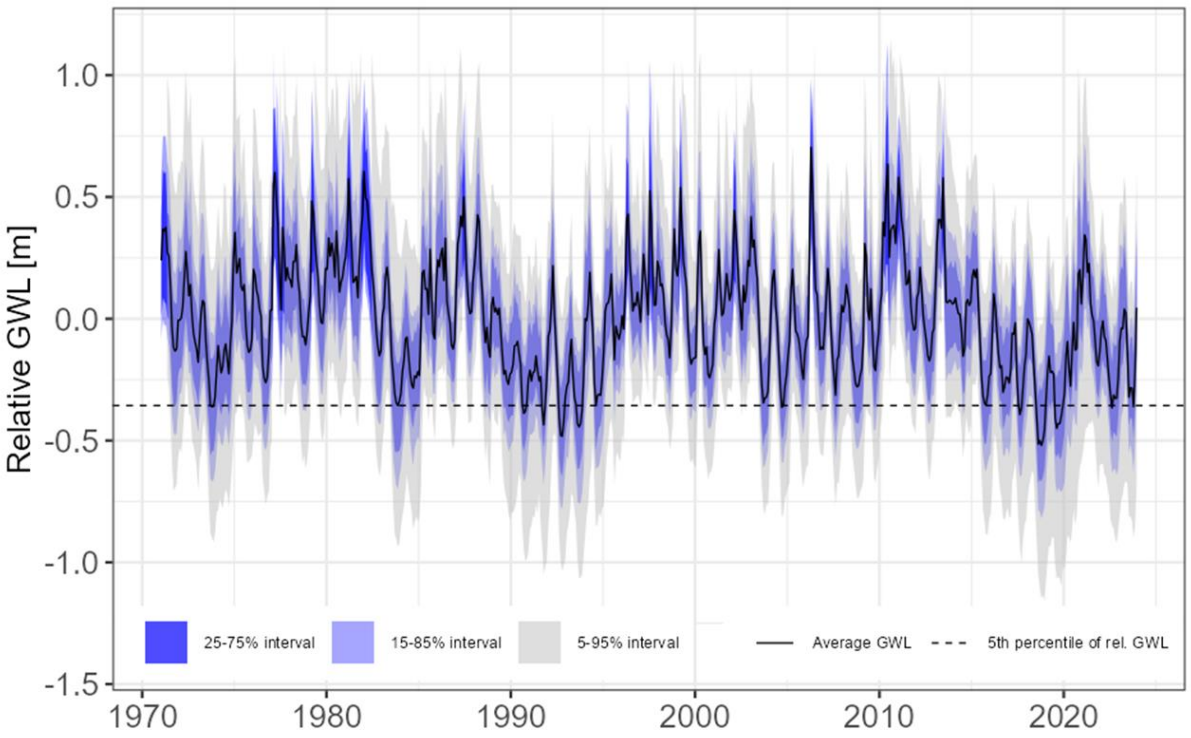


Fig. 1. Representative GWL hydrograph for all monitoring wells in Quaternary GWBs.

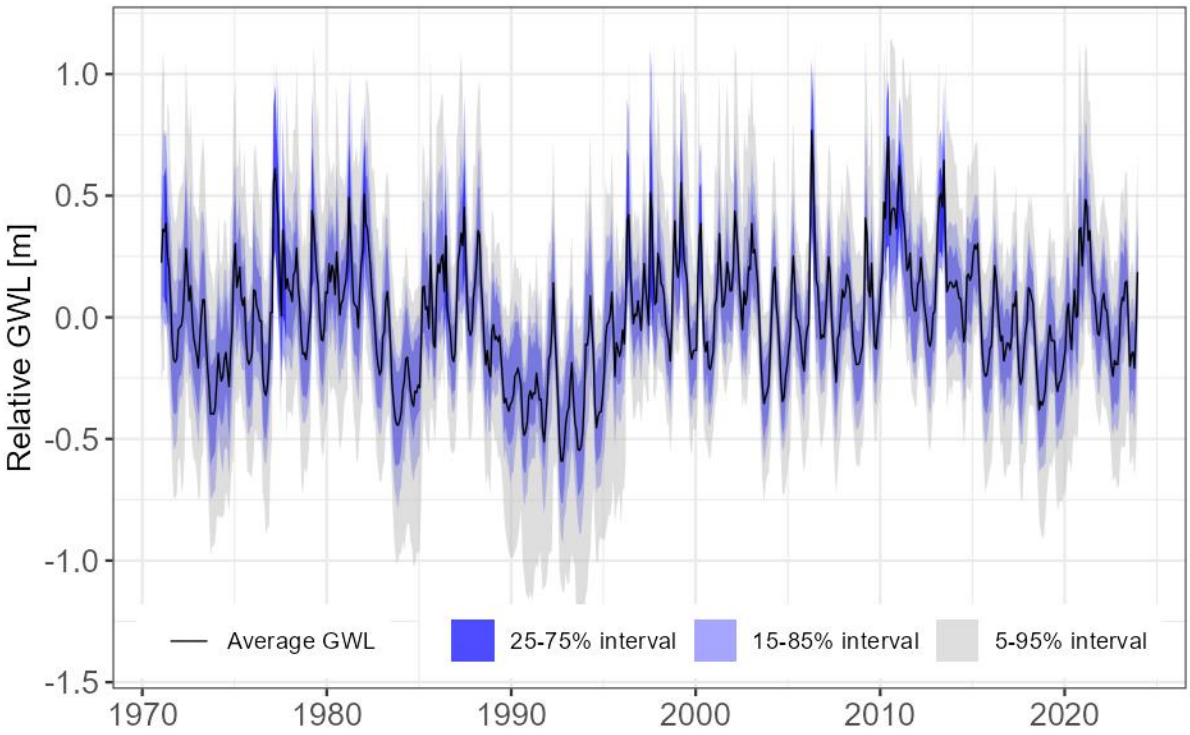


Fig. 2. Representative GWL hydrograph for monitoring wells exhibiting the greatest GWL decline during the 1990–1994 drought.

The lowest groundwater level in the representative hydrograph occurred during the 2015–2020 drought, reaching −0.52 m in October 2018. This was closely followed by the 1990–1994 drought, when the minimum groundwater level reached −0.50 m in October 1992, only 2 cm higher than the minimum recorded in 2018. Both minima occurred during the two longest drought periods.

The remaining major droughts exhibited remarkably similar minimum groundwater levels: −0.37 m during 2003–2004, −0.37 m during 1973–1974, −0.36 m during 1983–1984, and −0.35 m during 2022–2023. Consequently, the difference between the lowest groundwater levels observed during the various drought periods does not exceed 17 cm.

Although the representative groundwater level in October 1992 was only 2 cm higher than in October 2018, this pattern was not observed uniformly across all monitoring wells. A total of 206 wells (48%) experienced a greater GWL decline during the 1990–1994 drought than during 2015–2020, and this behaviour is reflected in a separate representative GWL hydrograph constructed for this subset of wells (Fig. 2).

In addition to the pronounced decline during 1990–1994, this subset also exhibited a significant GWL decrease in 1973, while the decline observed in 1983 continued into 1984. Groundwater levels during the droughts of 2003–2004 and 2015–2020 were approximately comparable. This distinct behaviour indicates that different groups of monitoring wells responded differently to historical drought events, suggesting variations in recharge mechanisms and hydrogeological conditions among Quaternary GWBs.

Baseflow

Baseflow was used as an indicator of groundwater recharge to Quaternary GWBs. Recharge was represented by groundwater inflows from the underlying basic-layer GWBs and from adjacent recharge GWBs located on surrounding valley slopes.

For these GWBs, the Czech Hydrometeorological Institute estimates baseflow using the Eckhardt digital filter. Monthly baseflow values from all GWBs that could potentially contribute groundwater inflow to Quaternary GWBs were summed and analysed (Fig. 3 and 4).

For drought conditions corresponding to the 5th percentile, monthly baseflow minima occurred in 1973, December 1983, September 1990, October 1992, December 2003, October 2015, and November 2018. Additional low monthly baseflow values were observed in September 2004, August 2022, and October 2023.

The annual average baseflow clearly reflects prolonged groundwater depletion during the 1990–1994 and 2015–2020 drought periods. During 1990–1994, the combined annual average baseflow from all recharge and underlying GWBs reached a minimum of approximately 110 000 l/s in 1991. During the 2015–2020 drought, however, baseflow decreased even further, reaching approximately 99,000 l/s in 2018 (Fig. 3).

Another noticeable reduction in annual baseflow occurred in 2004, although the annual total remained substantially higher than during the droughts of 1990–1994 and 2015–2020. Similarly, pronounced reductions were recorded in 2022 and 2023, but these values also remained above those observed during 2015–2020.

Overall, the temporal evolution of baseflow corresponds closely to the representative GWL hydrograph based on all monitoring wells. However, changes in baseflow from recharge and underlying GWBs do not explain the distinct GWL behaviour observed in the subset of wells that experienced their greatest decline during the 1990–1994 drought.

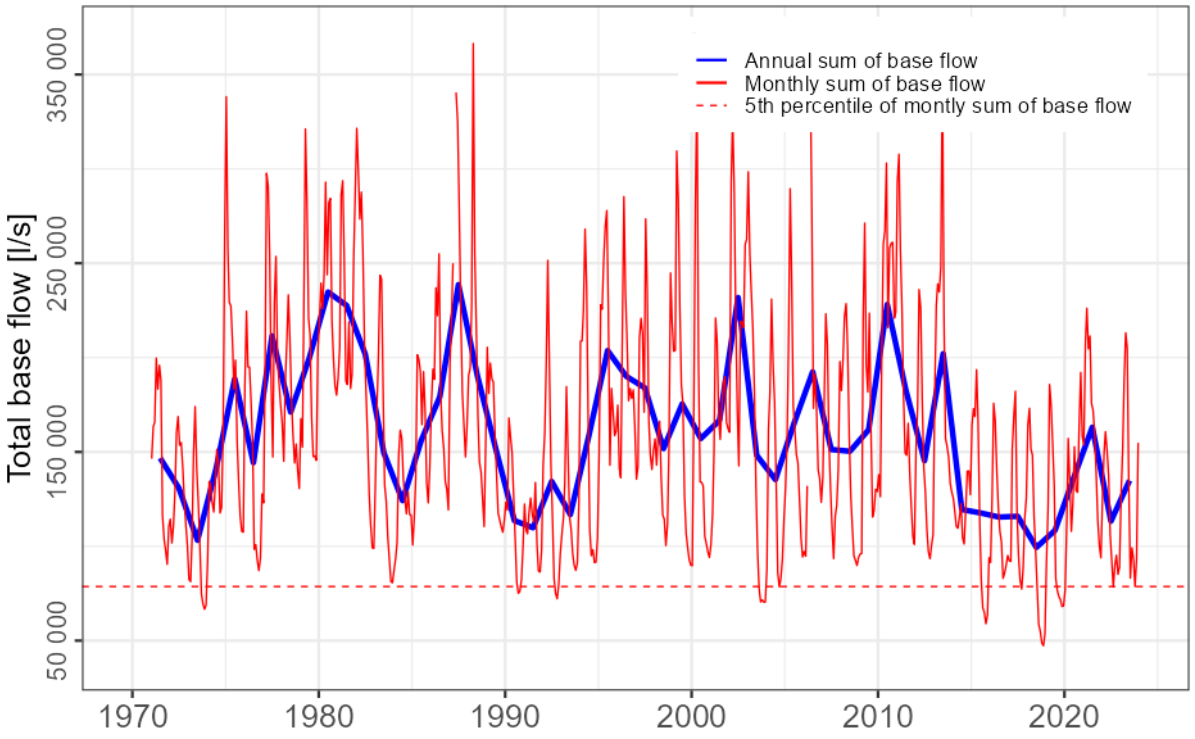


Fig. 3. Temporal evolution of baseflow in recharge and underlying GWBs supplying Quaternary GWBs.

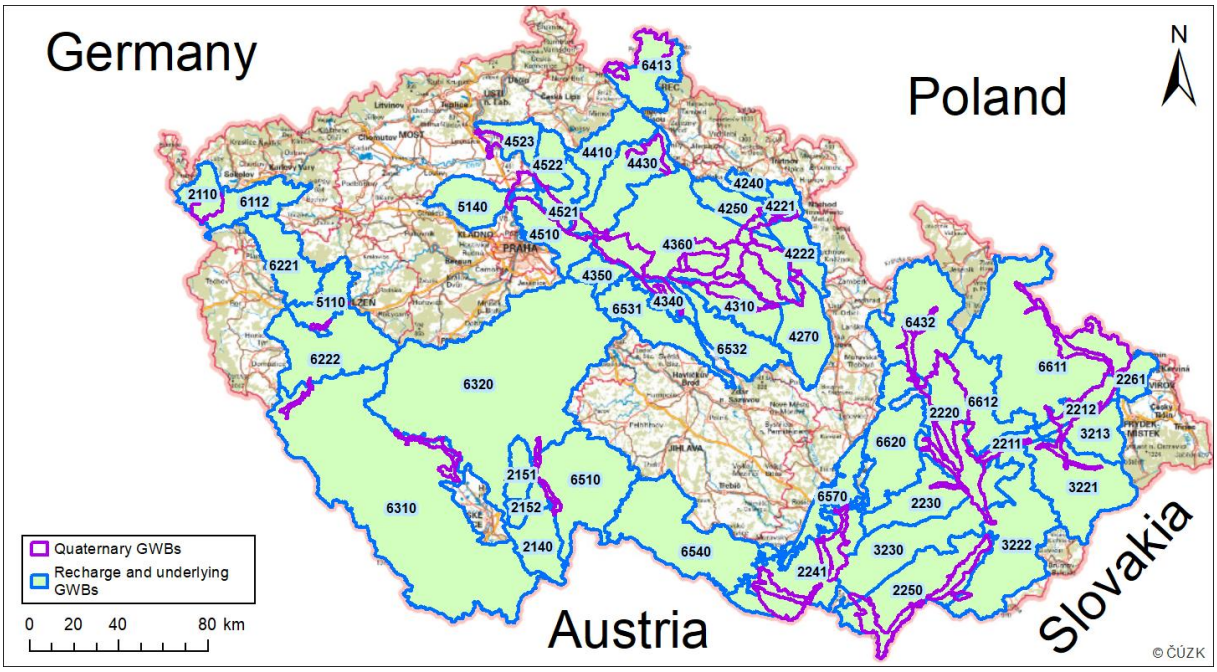


Fig. 4. Quaternary GWBs and the associated recharge and underlying GWBs used in the baseflow analysis.

Groundwater Abstractions in Quaternary GWBs

Historical groundwater abstraction data for Quaternary GWBs were obtained from the T. G. Masaryk Water Research Institute (TGM WRI). Two datasets were available. The first covers the period 2008–2022, with abstractions assigned to GWBs according to the 2005 groundwater body delineation. The second covers 1980–2007 but contains incomplete records and uses the 1986 groundwater body delineation.

Because the period 1990–1994 is of particular importance for evaluating the effects of groundwater abstraction, all abstraction records exceeding 1 l/s that lacked assignment to the current groundwater-body classification or spatial coordinates were manually reclassified into the corresponding sub-regions and Quaternary GWBs according to the 2005 delineation. In addition, a nationwide abstraction database maintained by TGM WRI was used to supplement the dataset with all abstractions exceeding 5 l/s, since not all abstractions hydraulically connected to Quaternary GWBs had historically been assigned to them. For each sub-region, the temporal evolution of groundwater abstraction was compiled and the completeness of the historical records was evaluated.

Groundwater abstractions located in the immediate vicinity of Quaternary GWBs were also assigned to the respective sub-regions if they were hydraulically connected to the Quaternary aquifer and occurred within the same hydrogeological environment. Conversely, abstractions located within Quaternary GWBs but exploiting deeper, non-Quaternary aquifers were excluded after verification using borehole documentation and archived hydrogeological records.

Groundwater abstraction rates have changed considerably since systematic records began. The maximum total abstraction from Quaternary GWBs and their immediate surroundings reached 6 777 l/s in 1989 (Fig. 5). During the drought period 1990–1994, the average abstraction amounted to 6 202 l/s. Thereafter, abstractions declined substantially, reaching an average of 3 221 l/s during 2015–2020.

Thus, average groundwater abstraction during 1990–1994 was approximately twice as high as during 2015–2020. This difference most likely explains why the subset of monitoring wells exhibited lower GWL during the earlier drought despite the more severe hydrological conditions observed in 2015–2020.

Methodology for Assessing the Quantitative Status

Many Quaternary GWBs contain several hydraulically independent well fields, while others are divided by major rivers. Consequently, numerous GWBs were subdivided into sub-regions, each of which was assessed independently.

For each sub-region, a standardized representative GWL hydrograph (sGWL) was developed by averaging standardized monthly groundwater levels from all selected monitoring wells within the sub-region. For each of the major drought periods (1990–1994, 2003–2004, and 2015–2020), the minimum standardized groundwater level (sGWLmin) was determined.

The assessment methodology is based on the relationship between sGWLmin during drought periods and the corresponding groundwater abstraction within each sub-region. The GWA rate at which groundwater levels did not decline below the selected threshold during a given drought period was defined as the verified resources. This value represents the abstraction criterion for evaluating the quantitative status of the sub-region. In total, 75 sub-regions were evaluated.

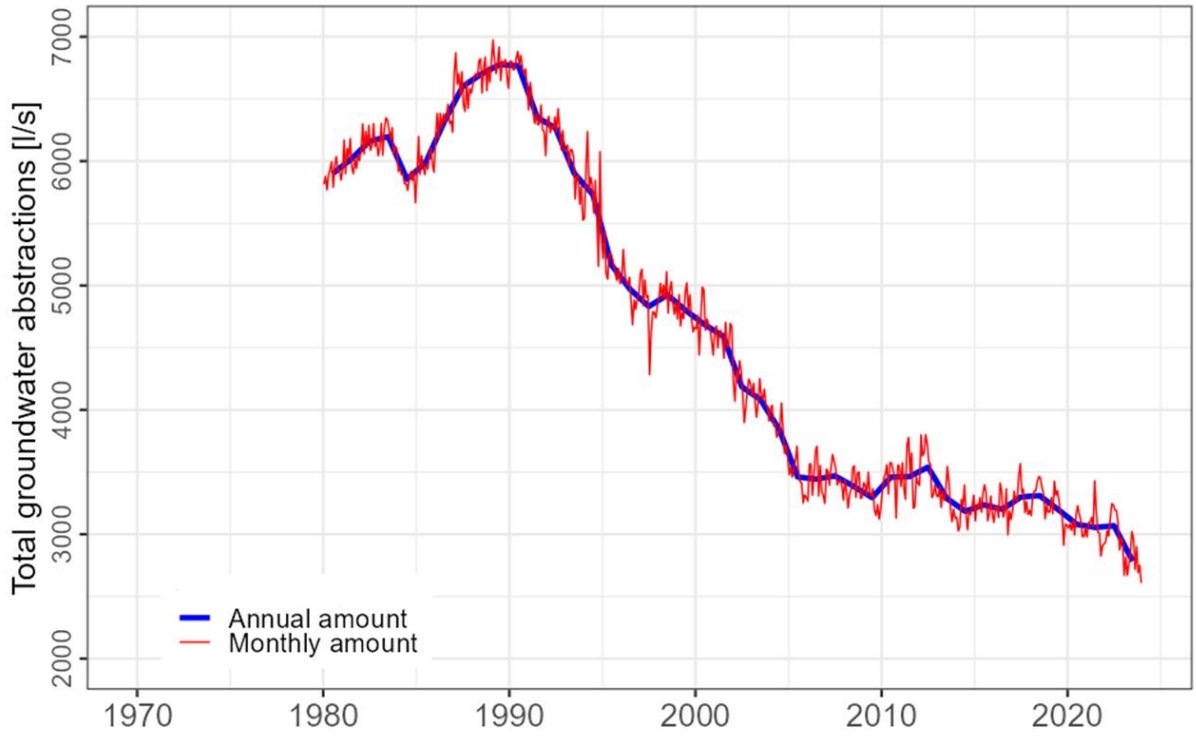


Fig. 5. Total groundwater abstractions from all Quaternary GWBs.

Where groundwater abstraction during 1990–1994 represented the historical maximum after 1990 and the corresponding sGWLmin remained higher than that observed during 2015–2020, the abstraction recorded during 1990–1994 was adopted as the verified groundwater resources (VRs). An example is Sub-region 111001, corresponding to Groundwater Body 1110 – Orlice Quaternary, where groundwater abstraction of 102 l/s in 1990 did not result in groundwater levels falling below those recorded during the 2015–2020 drought (Fig. 6). A total of 25 sub-regions were classified in this category. Their groundwater abstraction rates during 1990–1994 were considered sustainable because they did not cause groundwater levels to decline below the reference minimum observed during 2015–2020.

In some sub-regions, groundwater levels during 1990–1994 fell below those observed during 2015–2020 while groundwater abstraction was at its historical maximum. In other sub-regions, the highest groundwater abstraction occurred during 2003–2004. In both cases, the assessment was based on the 2003–2004 drought. If the sGWBmin during 2003–2004 remained above the minimum observed during

2015–2020, then groundwater abstraction during 2003–2004 was adopted as the verified resources. This category comprised 16 sub-regions.

A representative example is Sub-region 162301, corresponding to GWB 1623 – Blaty Pliopleistocene, where groundwater abstraction of 180 l/s during 1990–1992 contributed to groundwater levels falling below those observed during 2015–2020 (Fig. 7). In contrast, abstraction of 139 l/s during 2003–2004 did not cause groundwater levels to fall below the reference minimum. Consequently, the abstraction recorded during 2003–2004 was adopted as the verified resources.

Some sub-regions experienced their highest groundwater abstractions during 2015–2020. In these cases, where groundwater levels were also at their historical minima, it is not always possible to distinguish between the effects of severe drought and those of groundwater abstraction. Lower abstraction rates reported for 1990–1994 may have two explanations: groundwater abstraction genuinely increased over time or historical abstraction records from the early 1990s are incomplete. An example of the first situation is Sub-region 164401, corresponding to GWB 1644 – Morava Quaternary, where abstraction gradually increased from 22 l/s in 1992 to 31 l/s in 2015 (Fig. 8).

Conversely, Sub-region 164201 (GWB 1642 – Jevišovka Quaternary) exhibited lower groundwater levels during 1990–1994 despite apparently lower abstraction rates (Fig. 9). This discrepancy is most likely explained by incomplete historical abstraction records, suggesting that actual groundwater abstraction during the early 1990s was substantially higher than documented. These sub-regions were therefore evaluated individually by expert judgement. Where the standardized GWL hydrograph showed acceptable agreement with the representative GWL hydrograph, the abstraction observed during 2015–2020 was adopted as the verified groundwater resources.

For these sub-regions, the quantitative status is evaluated using two complementary criteria: verified resources (volumetric criterion) or minimum standardized groundwater level during 2015–2020 (GWL based criterion). The conjunction "or" indicates that satisfying either criterion is sufficient to classify the quantitative status as good. This approach is particularly important where current abstraction slightly exceeds the verified abstraction while groundwater levels remain above the reference threshold. Such situations generally occur in sub-regions with incomplete historical abstraction records or where current abstractions are already close to the maximum historically observed. A total of 23 sub-regions were assigned to this category.

The remaining 11 sub-regions lacked sufficient groundwater abstraction records and/or GWL monitoring to apply the general methodology. These sub-regions were therefore evaluated individually using case-specific approaches.

Conclusion

The proposed methodology evaluates the quantitative status of Quaternary GWB sub-regions by analysing the relationship between minimum standardized groundwater levels recorded during major drought periods and historical groundwater abstractions. This approach combines both GWL-based and volumetric-based criteria to provide a practical framework for assessing groundwater availability in hydrogeologically complex Quaternary aquifers (Nol et al. 2026).

Periods of elevated groundwater abstraction during drought conditions effectively verify the ability of the aquifer to sustain groundwater withdrawals. The maximum groundwater abstraction rate that does not result in groundwater levels falling below a selected reference threshold during a given drought period was defined as the verified resources. This value serves as the volumetric criterion for assessing quantitative status, while the corresponding minimum standardized groundwater level constitutes the GWL criterion.

The concept of verified resources does not imply identification or quantification of the recharge mechanisms supplying Quaternary GWBs. Recharge processes in these aquifers are complex, include

multiple sources of groundwater inflow, and may change over time in response to both natural conditions and groundwater exploitation. Instead, the verified resources concept provides an empirical estimate of groundwater availability based on the long-term response of monitored groundwater levels to historical abstraction during severe drought conditions.

By comparing minimum standardized groundwater levels during major drought periods with historical abstraction rates, volumetric and/or GWL criteria were established that define conditions under which the quantitative status of a sub-region can be considered good. The proposed methodology was successfully applied to 64 of the 75 identified sub-regions. For the remaining 11 sub-regions, groundwater abstraction records and/or GWL monitoring were insufficient to support the general methodology. These sub-regions therefore required individual expert assessment based on the available hydrogeological information.

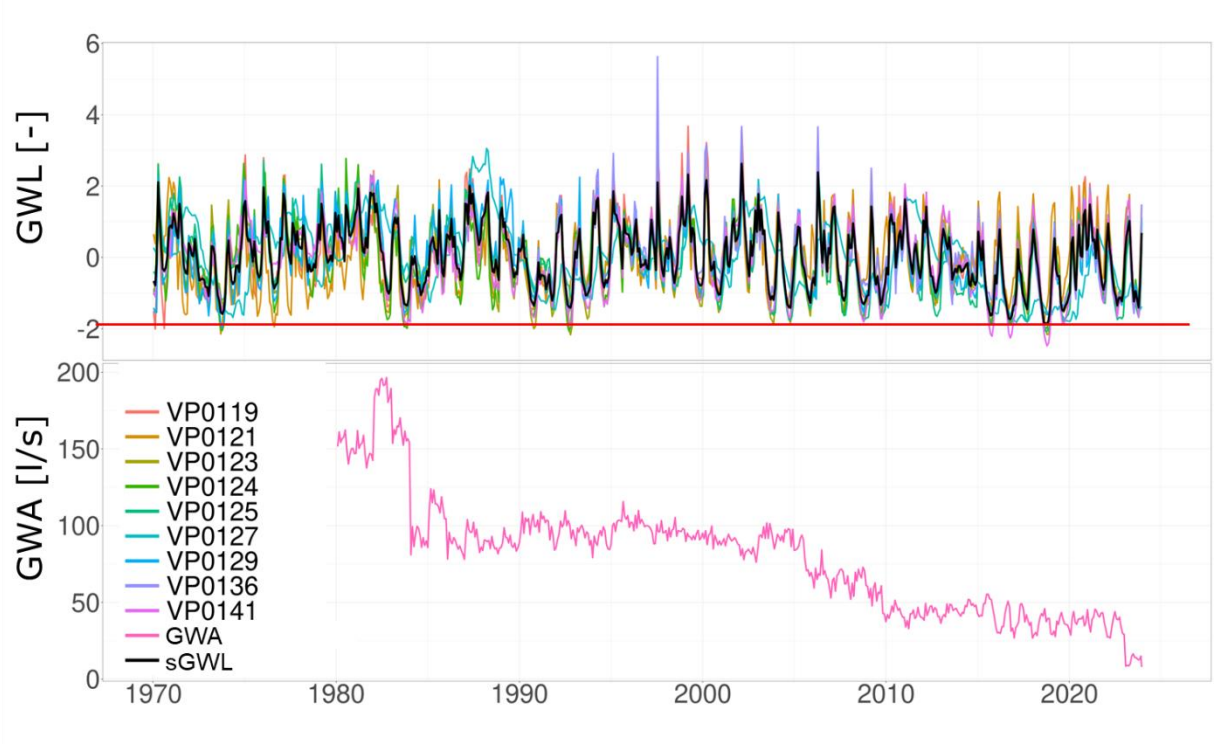


Fig. 6. Temporal evolution of groundwater abstraction (GWA) and the standardized groundwater level (sGWL) in boreholes (VPs) and sGWL in Sub-region 111001.

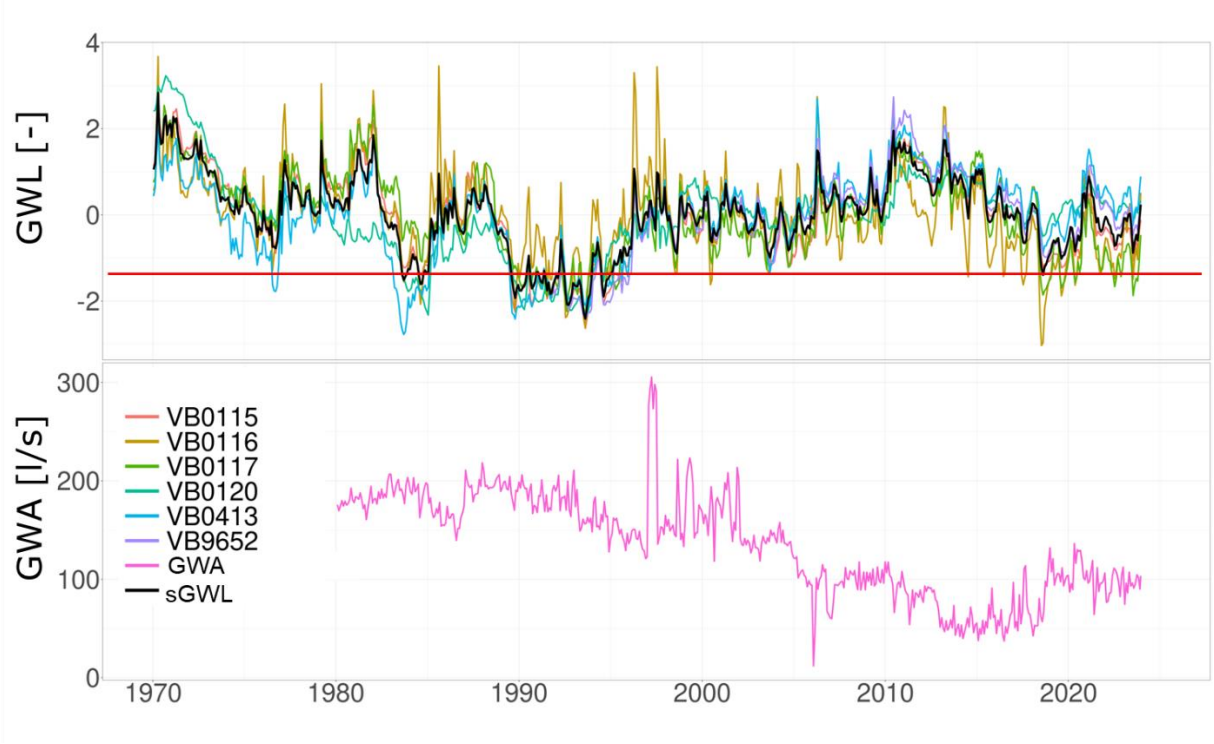


Fig. 7. Temporal evolution of groundwater abstraction (GWA) and the standardized groundwater level (sGWL) in boreholes (VBs) and sGWL in Sub-region 162301.

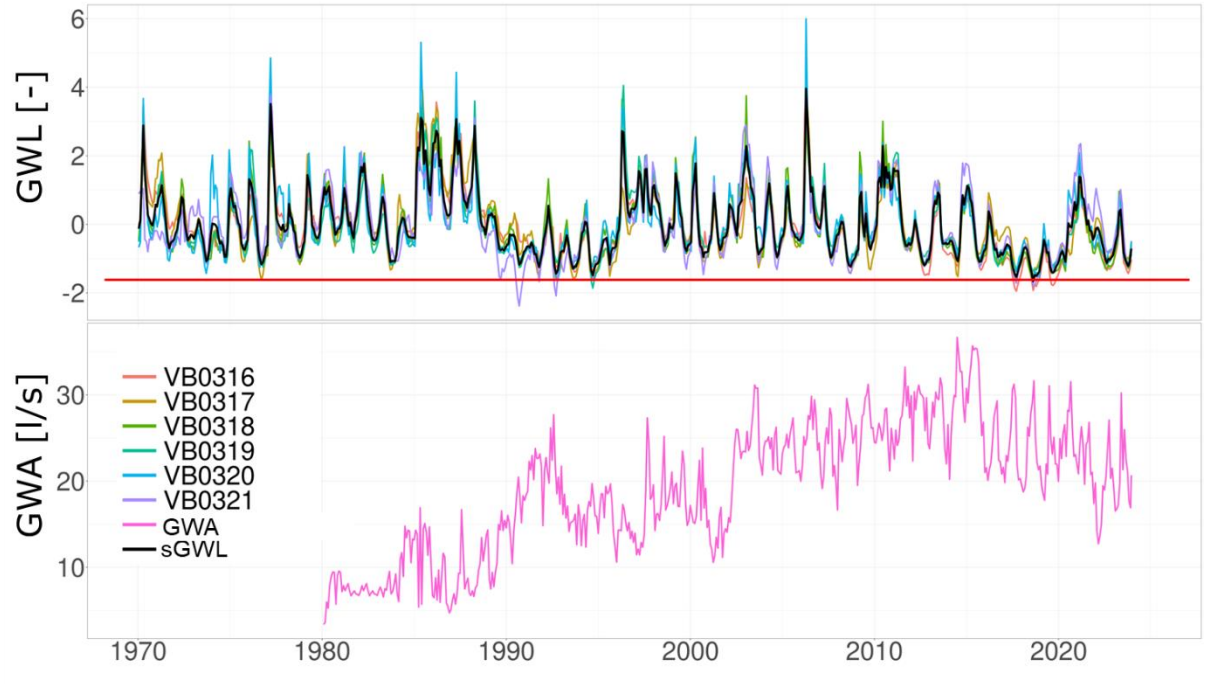


Fig. 8. Temporal evolution of groundwater abstraction (GWA) and the standardized groundwater level (sGWL) in boreholes (VBs) and sGWL in Sub-region 164401.

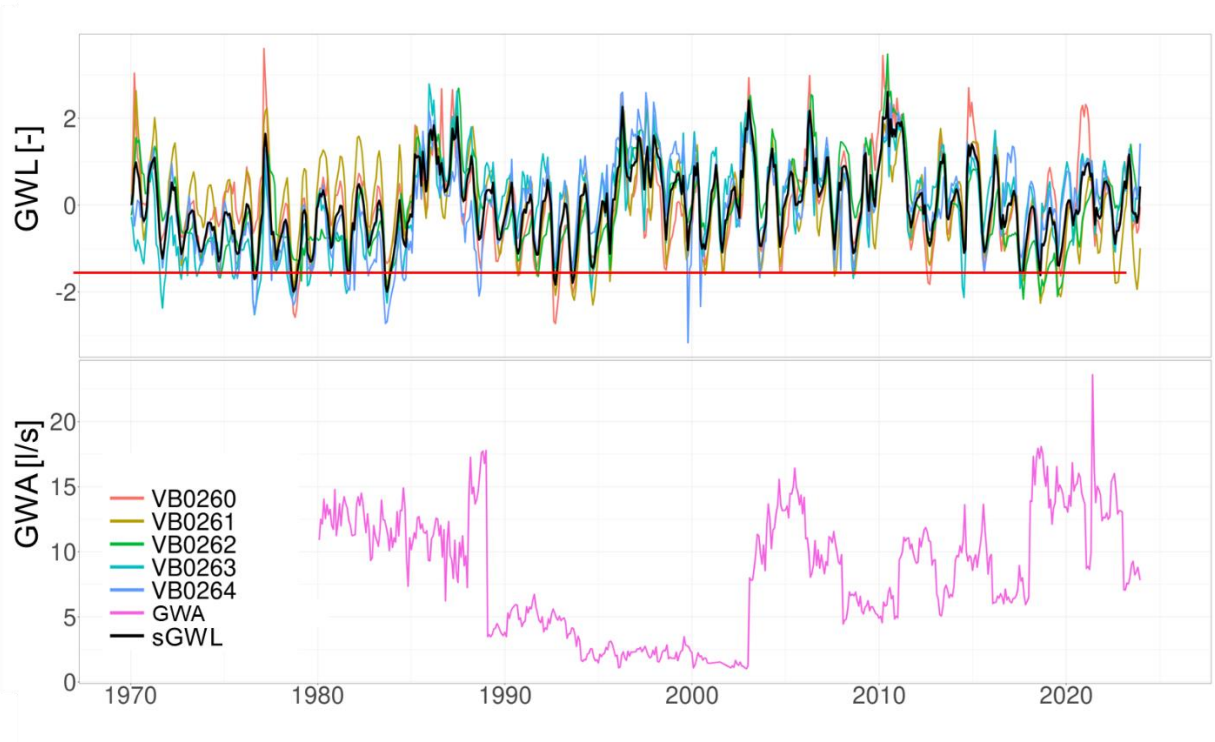


Fig. 9. Temporal evolution of groundwater abstraction (GWA) and the standardized groundwater level (sGWL) in boreholes (VBs) and sGWL in Sub-region 164201.

The subdivision of Quaternary GWBs into hydraulically coherent sub-regions proved to be an essential step for identifying the effects of groundwater abstraction and distinguishing them from natural GWL fluctuations. The methodology provides a robust and practical alternative to conventional groundwater balance approaches, which are often unsuitable for Quaternary aquifers because of their complex hydraulic interactions with adjacent aquifers and surface-water systems.

Overall, the proposed approach offers a transparent methodology for evaluating the quantitative status of Quaternary GWBs under the requirements of the EU Water Framework Directive (European Parliament and Council 2000), particularly in hydrogeological settings where conventional water-balance methods cannot be applied reliably.

Acknowledgments

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